Low-Carbon Hydrogen Economy Perspective and Net Zero-Energy Transition through Proton Exchange Membrane Electrolysis Cells (PEMECs), Anion Exchange Membranes (AEMs) and Wind for Green Hydrogen Generation

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Funding: No specific funding was received for this work.
Potential competing interests: No potential competing interests to declare.

Abstract

Even though there has been a rapid increase in the use of hydrogen production techniques in recent years, there is still an exigent need for affordable, sustainable and efficient low-carbon hydrogen generation methods. Based on the current United Nations Sustainable Development Goals, in recent decades, alkaline electrolysers and proton exchange membrane electrolysers have reached high commercial and industrial levels in the hydroprocessing industry. The energy generated from wind and solar energy is integrated with anion exchange membranes (AEMs) and proton exchange membrane fuel cells (PEMFCs), which produce clean hydrogen. Anion exchange membrane (AEM) electrolysers overcome the worst problems of previous types of electrolysers because of their ability to use nonplatinum and nonnafion membrane materials, high hydrogen storage density, and compact microcells recommended for large-scale low-carbon systems. Another technique for hydrogen production via oxidation is ethanol electrocatalysis in PEMECs for ultraclean hydrogen production. In this study, hydrogen production via water electrolysis with the help of anion-conducting solid polymer electrolytes and a novel integrated inorganic membrane electrode assembly (I2 MEA) for anion exchange membrane (AEM) water electrolysis by using inorganic Mg-Al layered double hydroxides (Mg-Al LDHs) as an ionic conductor were also theoretically and economically investigated for the purpose of producing low-carbon hydrogen.

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Keywords: Sustainable Development Goals, Economics, Hydrogen Energy, Anion Exchange Membrane, Proton Exchange Membrane Electrolysis Cell, Solar, Wind Energy, Low-carbon Hydrogen, Sustainability, Circularity.

1. Introduction

Low-carbon clean hydrogen energy is frequently viewed as an additional energy source for the future when there is greater than ever-demand for low-carbon technology. Hydrogen can be transformed into valuable forms of energy in a variety of ways due to decades of study and development. However, there are a few hydrogen-specific conversion technologies that are more effective and less harmful than traditional fuels (Boul 2022; Mohideen et al. 2021).

The necessity of reducing greenhouse gas (GHG) emissions to reduce the carbon footprint of the entire planet is driving considerable decarbonisation in industries worldwide (Mittal and Kushwaha 2024). Switching to low-carbon technology in the current environment is challenging and intimidating because it involves significant financial outlays, new installations or changes, and rising energy bills and demands. Decarbonisation options are now accessible; however, they are still relatively new and severely need standardisation, technical progress, skilled labor, and roadmaps (Singh R.P and Kushwaha O.S 2013; Arya et al. 2021).

The goal of mitigating decarbonisation in the energy sector is to reduce greenhouse gas emissions in the atmosphere. Following the 2015 Paris Agreement on Climate Change, nations have shown significant interest in reducing CO_2 emissions. By 2017, there was an increase in CO_2 emissions to 2.7 ppm/year on average compared to the 1.3 ppm/year emissions between 1960 and 2000. **Figure 1** shows the percentages of different greenhouse emissions from 1990 to 2023. The global investments in global energy investments for the law of the carbon economy are also indicated in **Figure 1** (Intergovernmental Panel on Climate Change 2015; Kumar et al. 2022; International Energy Agency 2022). Currently, hybrid and electric vehicles make up a substantial and growing share of automobile sales. In terms of engine design, fuel economy, fuel composition, and internal combustion engines, affordable and sustainable methods are undergoing more subtle changes.

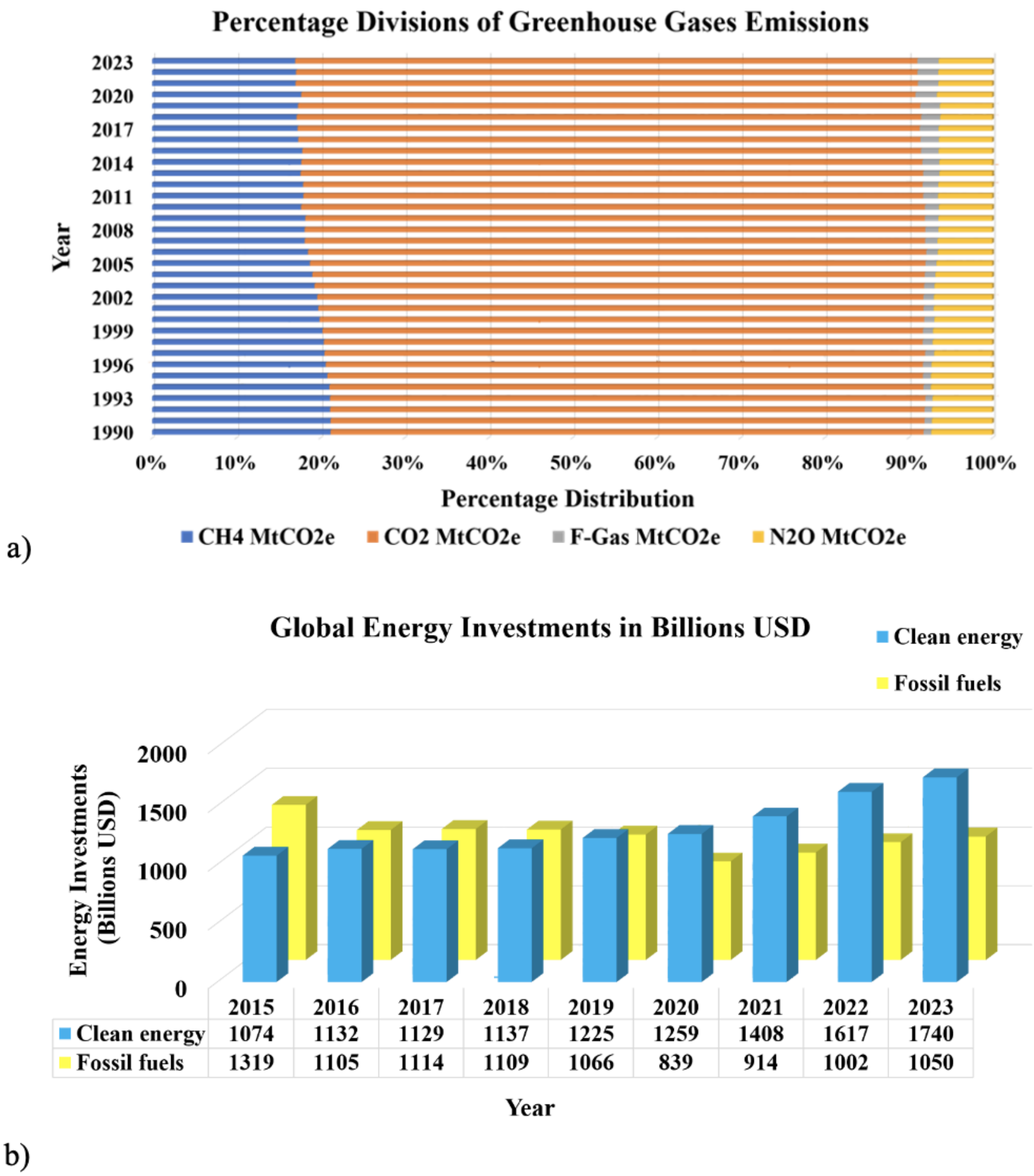

Figure 1. a) Percentage divisions of greenhouse gas emissions from 1990-2023 and b) global energy investments toward low-carbon energy sources in 2023. (Intergovernmental Panel on Climate Change 2015; Kumar et al. 2022; - International Energy Agency 2022)

Hydrogen and fuel cell technologies are vital for transitioning from fossil fuels to zero-carbon energy systems and improving local air quality. When burned with oxygen, hydrogen has a high energy density and emits no carbon dioxide, with a 142 MJ kg^{-1} energy density. The demand for hydrogen has been steadily increasing since the 1970 s to 2024. However, the synthesis of hydrogen is currently hampered by coal and natural gas, both of which contain CO_2 as a byproduct. Although renewable hydrogen is now cost-competitive, its price may soon change, reducing the need for fossil fuels. **Figure 2** depicts the sharp increase in the demand for hydrogen as an energy source (Chu et al. 2022; C. Park et al. 2022).

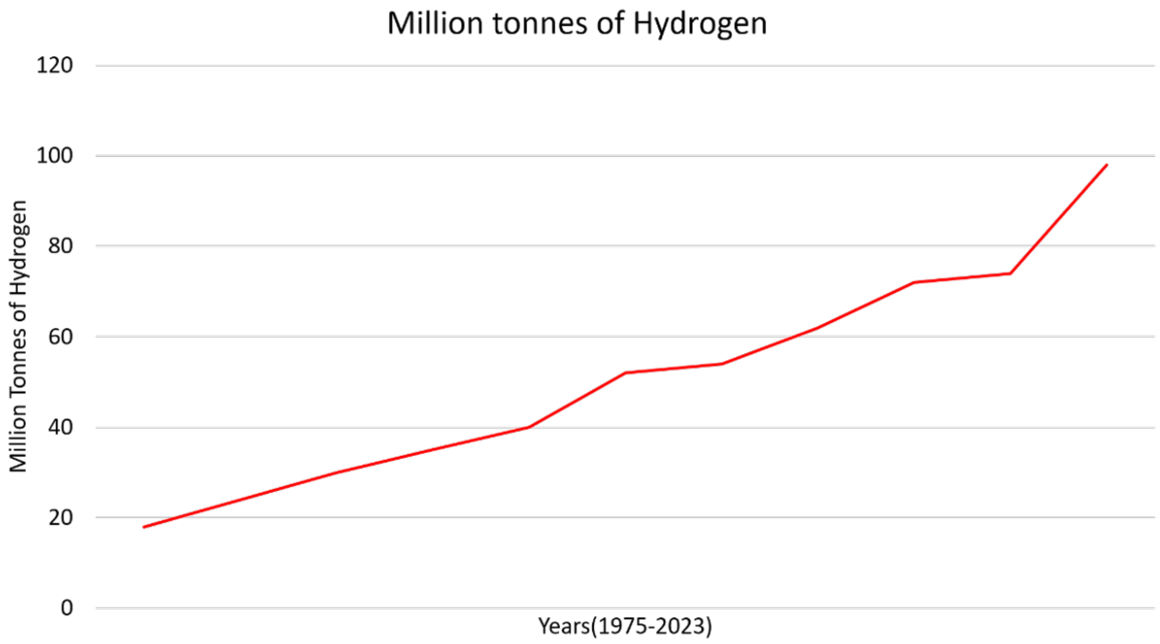

Figure 2. Global annual demand for hydrogen from 1975 to 2023. (Chu et al. 2022; C. Park et al. 2022).

1.1. Green Hydrogen

Several methods, including the electrolysis of water and coal, steam reforming of natural gas, production of H_2 from petroleum, and coal gasification, are used to create hydrogen. Methane and steam combine at temperatures between 700 and 1000 °C during steam reforming to create hydrogen and carbon monoxide(Atilhan et al. 2021; Panchenko et al. 2023). The carbon dioxide produced by the water-gas shift reaction has a CO_2 intensity of 5.5 kg CO_2/kg H_2. In 2019, 70 million tons of hydrogen were produced annually, the same as 275 million tons of oil (W. Zhang and Chiu 2020). However, hydrogen is regarded as a significant energy source for the future. By 2050, according to the NEF, 24% of the energy mix may be produced. Hydrogen is a strong option for reducing the volume of current coal/fossil fuel furnaces, which is a goal for industries that make products such as cement and steel that are aiming to minimise their carbon footprint and globalise their low-carbon hydrogen energy using alternative fuels such as green hydrogen (Velazquez Abad and Dodds 2020; Gondal, Masood, and Khan 2018).

Currently, 23% of hydrogen is generated from coal, and 76% is generated from natural gas (Peschka 1992). Fossil fuels meet most hydrogen energy needs and are primarily used to refine oil and make fertiliser ammonia. An extra 45 million tons of hydrogen are utilised industrially without separating it from other gases (Chew et al. 2023; Leachman et al. 2009; Veras et al. 2017). Approximately 830 million tons of carbon dioxide ($MtCO_2$/year) are released into the atmosphere due to the creation of hydrogen, which is comparable to the combined CO_2 emissions of Indonesia and the UK (Y. Zhang et al. 2008; Baykara 2018). When employed in energy applications, hydrogen emits no carbon, but the processes necessary to manufacture it produce CO_2 emissions (Basheer and Ali 2019). Within a decade, hydrogen consumption could overtake other indirect greenhouse gas contributors due to its rising demand and megaproject proposals that include hydrogen-based civilisations and economies. The energy source utilised to produce hydrogen is extremely important in this direction since only environmentally friendly and cost-effective hydrogen can be produced using greener energy sources. The gray, blue, green, brown, and turquoise hydrogen are the different color-coded subcategories of hydrogen. Grey hydrogen is produced by steam-reforming natural gas, whereas blue hydrogen requires CCS to collect and store 70–95% of the CO2. Green hydrogen uses only sustainable water energy, while turquoise hydrogen is created by pyrolysing methane. Brown hydrogen is created by utilising coal.

1.2. Why a Need for a Low-Carbon Hydrogen Energy Perspective

There have been a large number of patents, research papers, and perspectives on conventional hydrogen production or expensive low-carbon hydrogen generation techniques. There is still an urgent need for sustainable, efficient, and affordable low-carbon hydrogen production techniques. Such needs can be met only once thorough research and analysis are performed for low-carbon hydrogen. Such research should be first driven by life cycle assessments of different production techniques, environmental impact assessments, and computational analyses of several production, storage and risk assessments. Once such analysis is complete, then the low-carbon hydrogen production and storage methods should undergo sustainable laboratory-scale experimentation before proceeding toward the final stage of efficient, affordable and sustainable techniques for hydrogen production and storage for pilot-scale industrial, industrial-institutional and educational institutional projects. Once such pilot-scale low-carbon hydrogen projects are successfully established, only such hydrogen energy techniques can be commercialised for sustainable low-carbon economy circulation. **Figure 3** shows the number of publications, which include literature reviews, patents and research papers on low-carbon hydrogen energy from 1975 to 13th February 2024.

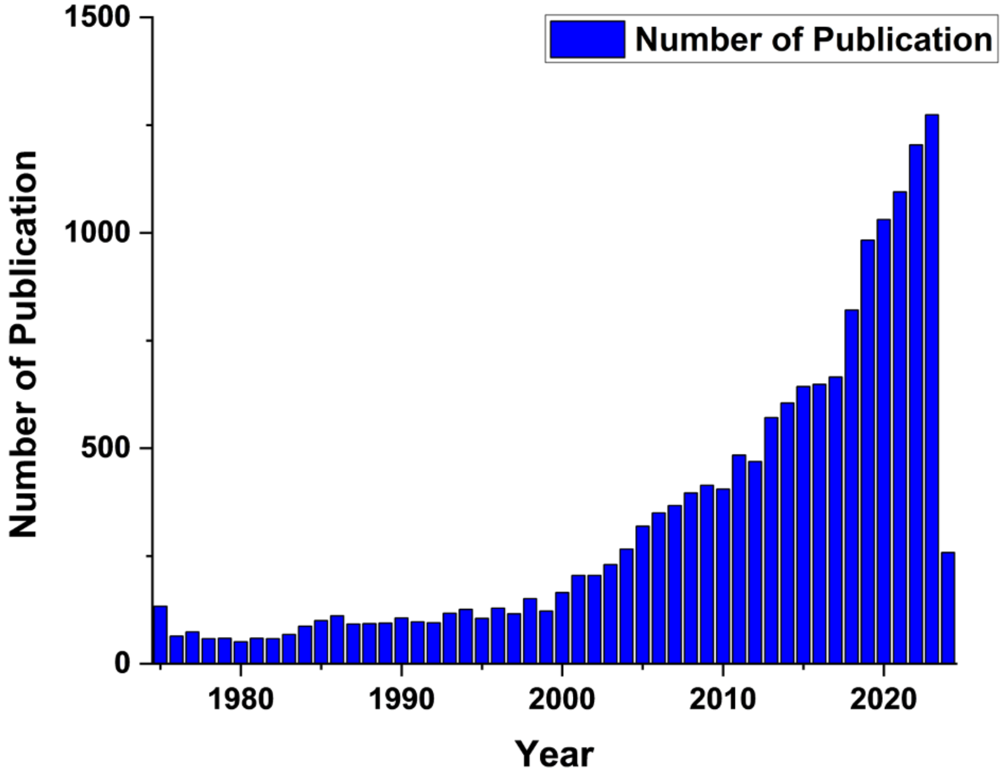

Figure 3. Number of Publications from 1975-2024 for low-carbon hydrogen energy.

2. Economic Aspects of Green Hydrogen

Green hydrogen, which will be sold between US$1.5 and US$3.4 per kilogram in 2023, is used in the manufacturing of methanol, electricity generation, fuels and ammonia. However, because it is made from fossil fuels, CO_2 emissions increase. According to IRENA, green hydrogen has a CO_2 capture efficiency of at most 85–95%, which results in 5–15% CO_2 emissions(Clark and Rifkin 2006). The cost of producing one kilogram of green hydrogen, which is derived by hydrolysing water, ranges from $3 to $7. According to Bloomberg New Energy Finance, the cost of green hydrogen will decrease to $1.60 to $2.60 in 2030 and $0.8 to $1.60 in 2050 (Oliveira, Beswick, and Yan 2021). While net neutral carbon-based green, turquoise, and blue hydrogen can produce CO_2-reduced hydrogen, research on nanomaterials is crucial for the generation and storage of hydrogen, which will help reduce costs (Dillman and Heinonen 2022; Sherif, Barbir, and Veziroglu 2005; Chew et al. 2023; Bockris 2013; Tseng, Lee, and Friley 2005). The detailed sustainable hydrogen supply chain management scheme is shown in **Figure 4**. This method works on the basis of input data delivery, mathematical modelling approach formulation and result analysis (Eh et al. 2022).

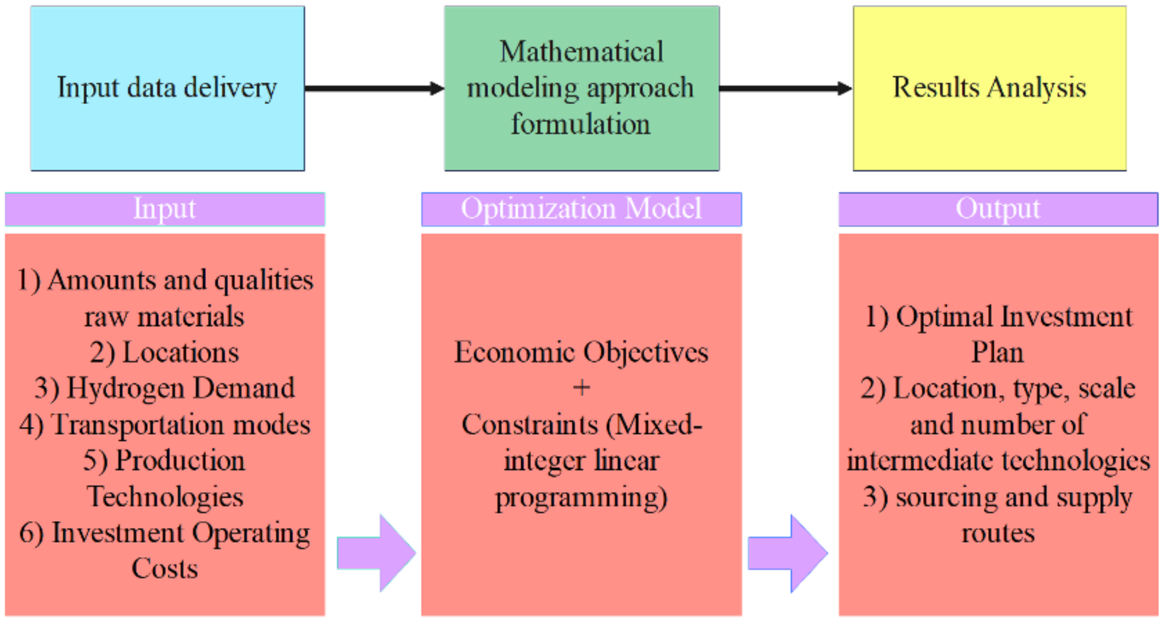

Figure 4. Sustainable Hydrogen Supply Chain Management (Eh et al. 2022)

To analyse the low carbon hydrogen potential, thorough statistics of the current global market of hydrogen demand in billions USD are necessary. **Figure** 1 shows the compound annual growth rate pattern from 2022 to 2023; based on these statistics, a compound growth of market demand growth is projected until 2028 for a 10.2% compound annual growth rate (CAGR) value (Bossel and Eliasson, 2022; Demirbas 2017).

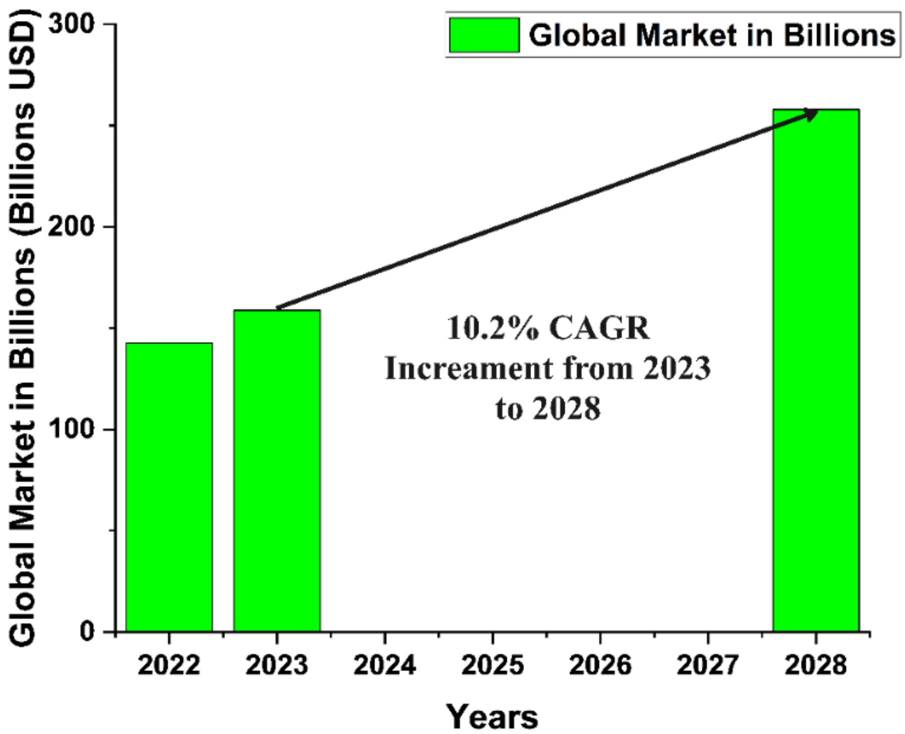

Figure 5. Global market value of hydrogen demand from 2022 to 2028 (projected) (Bossel and Eliasson, 2022; Demirbas 2017).

3. Electrolysers used in the Production of Low-Carbon Clean Hydrogen

Only 0.1% of the world's hydrogen is now produced using the age-old process of electrolysis (Ursua et al. 2012; Schmidt et al. 2017; Naimi and Antar 2018). power is used to divide water into hydrogen and oxygen, and based on the carbon footprint of power, highly pure hydrogen can be created. Green hydrogen can be produced and used as fuel in end uses, such as fuel cell cars, by integrating highly renewable energy sources (REVs), such as solar and wind photovoltaics (Liu et al. 2022; M. Yu et al. 2021; Hermesmann and Müller 2022). However, electrolysis requires 9 litres of water to produce 1 kg of cleaner hydrogen, which can result in a high water demand (Yue et al. 2021; Proost 2019; Arsad et al. 2023).

Each compartment in the highly modular structure of the electrolyser has 100 cells and dead plant material. This structure is very useful for the low-carbon hydrogen industrial scale-up process of hydrogen generation; compared to proton membrane electrolysis (PEM) and solid oxide electrolysis (SOE), alkaline electrolysers are more advanced but require less of an investment (Pastore et al. 2022; Marshall et al. 2007; Pletcher and Li 2011). PEM electrolysers have higher working loads and current densities, whereas SOEs are still in their infancy. Alkaline electrolysers currently cost between $500 and $1,400 per KW to create hydrogen, PEM electrolysers cost between $1,100 and $1,800 per KW, and SOE electrolysers cost between $2,500 and $5,600 per KW. The cost of electrolysers can be decreased to less than $400/KW by increasing their capacity to 70 GW (Lechartier et al. 2015; Ni, Leung, and Leung 2008). To meet these criteria, it is also necessary to produce affordable membrane and electrode materials. Great progress has been made in the field of proton exchange membrane fuel cells (PEMFCs) over the past decade due to their high efficiency, cleanliness, and zero carbon footprint (Tymoczko et al. 2016). However, the high cost, insufficient power density and durability of these materials are major obstacles to their commercialisation and could also be major disadvantages in the industrialisation of low-carbon hydrogen (Hitch and Dipple 2012; Bobicki et al. 2012; Griffiths et al. 2021; Taji et al. 2018).

4. Wind Mill for Low-Carbon Hydrogen and Power Generation

Like electricity, hydrogen can be produced from any energy source, including renewable energy sources. By making a number of adjustments, a wind energy source, such as a wind mill, can also be used to generate electricity and hydrogen (Khalilnejad and Riahy 2014; Rodrigues et al. 2015). An electrolyser is essential for producing hydrogen from any electrical source because it combines electricity and water to produce hydrogen and oxygen(Joselin Herbert et al. 2007; Blanco 2009; Sherif, Barbir, and Veziroglu 2005; Mostafaeipour et al. 2016; W.-J. Yang and Aydin 2001). The water supply, power electronics, controller, and cell stack are the four fundamental parts of an electrolyser **[Figure 6 A)]** (Martinez et al. 2018; Pastore et al. 2022). A stack of electrolytic cells absorbs clean water and electricity and uses that electricity to split water molecules into their building blocks, hydrogen and oxygen. Electrically, the electrolyser appears as a voltage source with series resistance based on **Figure 6 B)** (Schrotenboer et al. 2022; Rezaei, Naghdi-Khozani, and

Jafari 2020).

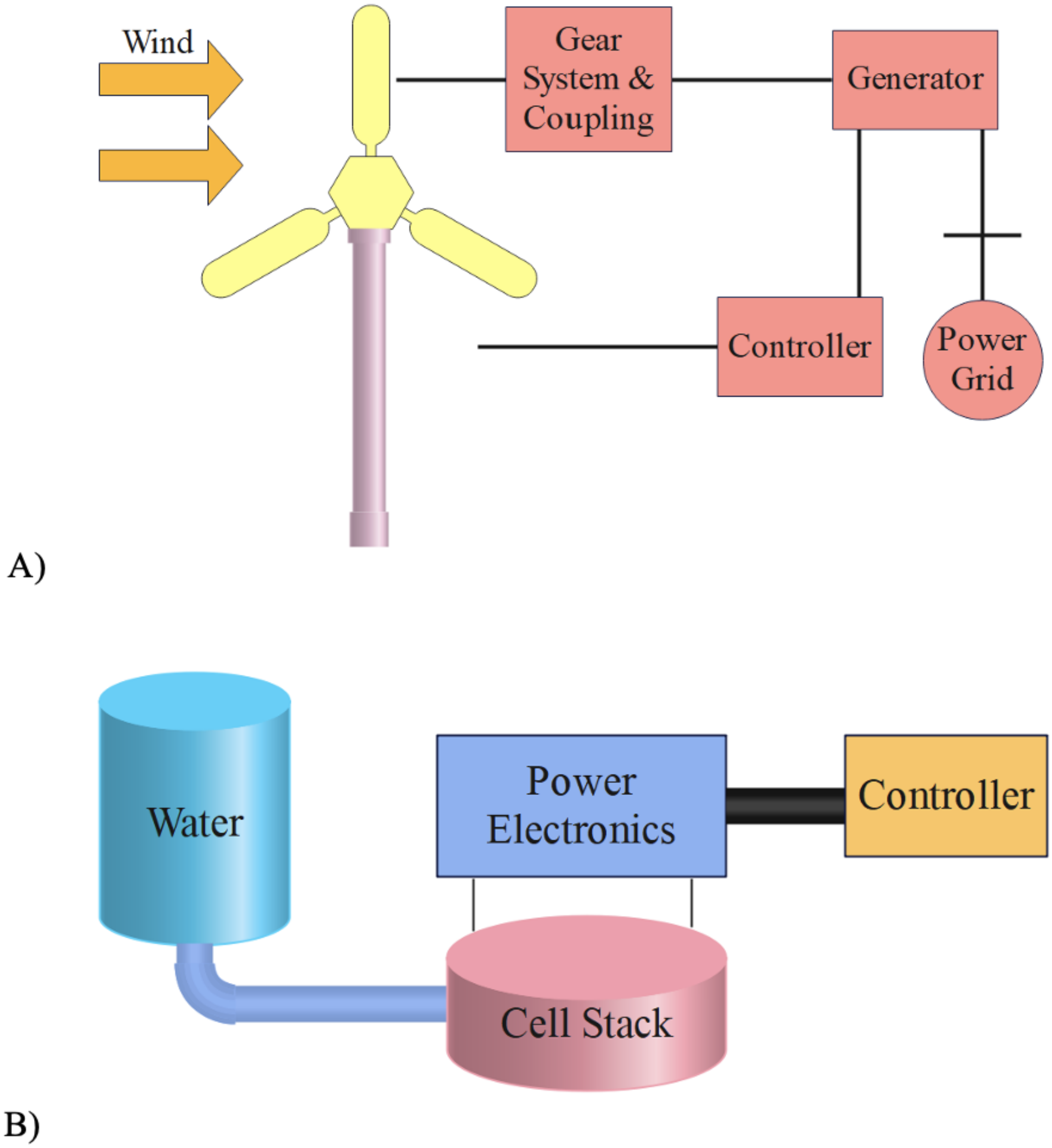

Figure 6. A) Wind turbine system flow diagram and B) general electrolyser configuration(Schrotenboer et al. 2022; Rezaei, Naghdi-Khozani, and Jafari 2020)

A wind turbine transforms wind energy into mechanical energy, which is subsequently increased in speed and sent to the generator rotor, where it is converted into electrical energy by the gear and coupling system(G. Zhang and Wan 2014; Burkhardt et al. 2016; Armijo and Philibert 2020). The controller detects the generator's power, temperature, wind speed, and direction **[Figure 4 A]** and initiates the relevant control signals to take control action. To connect to the grid, modern wind turbines utilise a control system along with power electronics. The controller and power electronics system of the turbine may also be used to control the electrolyser, avoiding the need for a second component. As there would be only one electrical conversion (from AC to DC), a connected system such as this would be less expensive overall and more efficient (Olateju and Kumar 2011; Garmsiri, Rosen, and Smith 2014; Salman and Teo 2003). Due to its free fuel expenses, wind power has a very low marginal cost, making it one of the better alternatives for the production of affordable, low-carbon, clean hydrogen energy generation products (Snyder and Kaiser 2009).

5. Power Electronics Configuration: A nearly infinite number of power electronics topologies can be used on a wind turbine

The diode bridge serves as an interface to a permanent magnet or an electrically excited synchronous generator in the first arrangement **(Figure 7a)**. The advantages of variable-speed operation are diminished because the electrolyser runs at a virtually constant voltage and almost constant speed. As a result, this strategy is probably not ideal. A full-processing or "back-to-back" converter is depicted in the second configuration **(Figure 7b)** (Frede Blaabjerg and Ke Ma 2013; Frede Blaabjerg, Liserre, and Ma 2012; Hansen 2012). For variable-speed wind turbines, this is arguably the converter type that is utilised the most frequently. This system can independently adjust the voltage on the DC busbar and the current entering the grid. The DC bus voltage regulates the capacity of an electrolyser if it is connected in parallel to a DC bus capacitor (F. Blaabjerg et al. 2011). The turbine and the electrolyser can be independently managed in this fashion. A matrix converter is displayed in the third arrangement **[Figure 7c]**. As shown on the left, an H-bridge is used in each switch cell in the matrix. A DC capacitor that can control voltage is built into each H-bridge. The generator and the electrolyser can once again be controlled individually by connecting an electrolyser in parallel with each capacitor. It might not be problematic to have many smaller electrolysers instead of one large electrolyzer, despite the extra complexity. Numerous individual cells are often grouped in series and joined in parallel to form electrolysers. As a result, with this design, each of the separate parts of the typical electrolyser will only be connected to its own matrix switch. Both times, the electrolytic system is managed by a turbine controller (Fingersh 2003). The cost of the electrolyser can be decreased with little to no increase in the cost of the wind turbine by eliminating the control unit and power electronics from the electrolyser, which is one of the advantageous economic perspectives for accessing low-carbon hydrogen. Additionally, the efficiency will increase as a result of the removal of the two power conversion processes (from the DC bus back to the AC and from the AC grid back to the DC). The overall performance can improve by 6% to 10% because each stage results in a loss of approximately 3% to 5%.

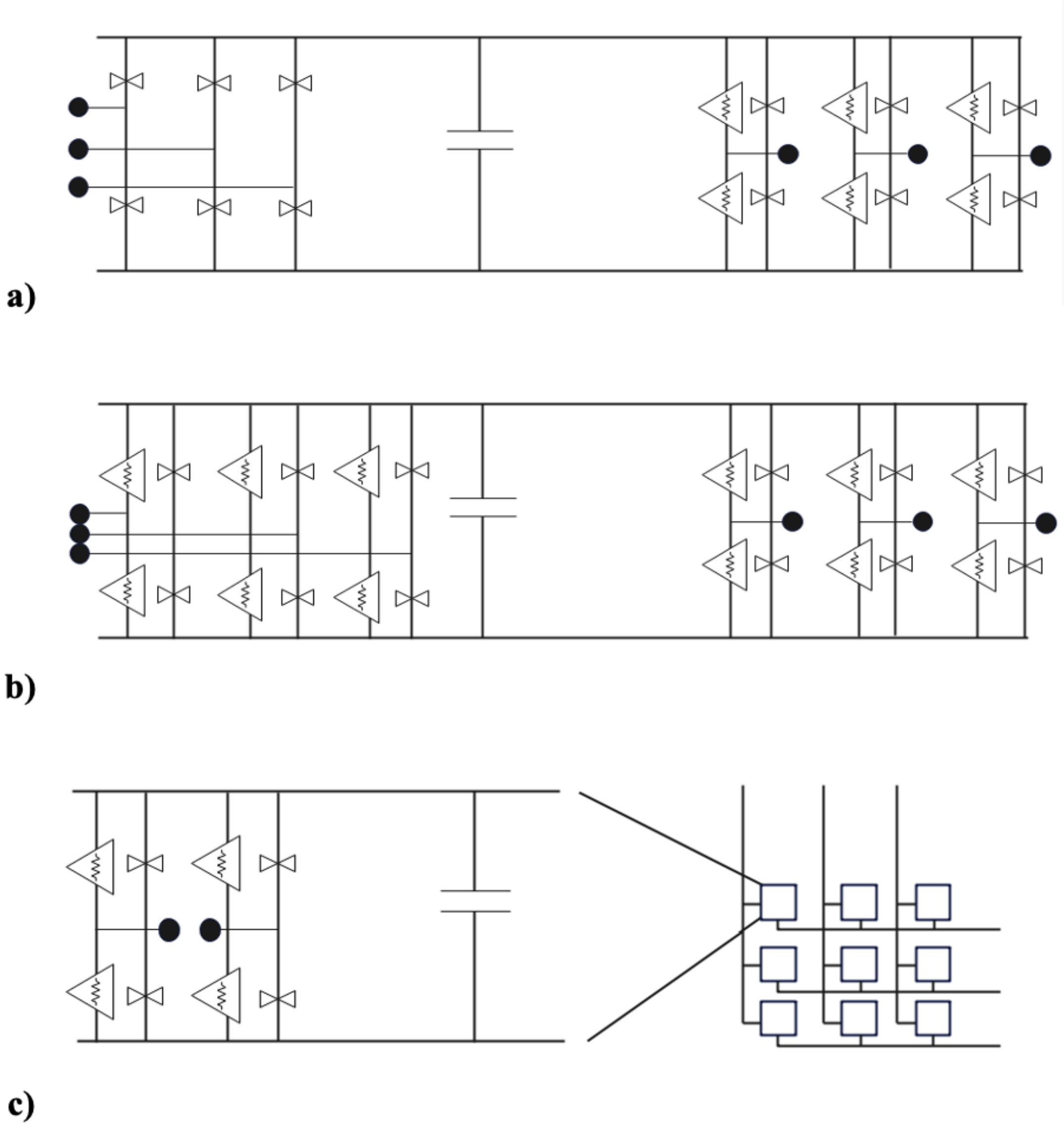

Figure 7. a) Diode bridge, b) back-to-back converter and c) matrix convertor (F. Blaabjerg et al. 2011; Hansen 2012; Frede Blaabjerg, Liserre, and Ma 2012)

5.1. Using Towers for Hydrogen Storage

Modern 1.5 MW wind turbine towers are typically 65 to 85 metres high, taper 5 to 2 metres in diameter from the bottom to the top, and have walls that are 25 to 36 mm thick (Zhuang et al. 2023; Gao et al. 2014). The storage capacities of these towers range from 663.7 to 867.9 m^3. It is possible to construct a hydrogen tank with a volume ranging from 442.5 m^3 to 578.6 m^3. Such a tank could hold hydrogen at capacities ranging from 4,425 Nm3 to 5,786 Nm^3 and would have a minimum pressure of 10 atmospheres. Each tower can carry between 399 kg and 521 kg of hydrogen, assuming that 11.1 Nm^3 of hydrogen is equivalent to 1 kg of hydrogen at standard temperature and pressure (F. Blaabjerg et al. 2011). A 1.5 MW wind turbine tower could store 13.3 MWh to 17.3 MWh (LHV) of hydrogen because of the lower heating value (LHV), which is approximately 33.3 kWh/kg. To produce 1 kilogram of hydrogen, the electrolyser needs 49.25 kWh at an efficiency of 80% (HHV = 39.4 kWh/kg). As a result, one tower has the capacity to store 13.1 to 17.1 hours of turbine running at full power. Countermeasures for hydrogen embrittlement will likely increase the tower's cost, which could be a drawback for the generation of affordable yet efficient hydrogen products.

5.2. Full System

Turbines, electrolysers, batteries, and power generation units such as fuel cells or combustion apparatuses can all be found in comprehensive systems. Additional optimisation opportunities are provided by integrating these devices into the turbine **[Figure 8]**.

While the battery and electrolyser are regulated by the DC bus voltage, the fuel cell or combustion chamber is mechanically or chemically managed. The device that is connected to the DC bus is determined by a multipole switch (Q. R. S. Miller et al. 2013). The tower can be used to store and release hydrogen from electrolysers and fuel cells, and all equipment is controlled by turbines and power electronics. A wind farm's hydrogen collection network can be used to transport hydrogen from one turbine to another and vice versa, increasing the options available for storage, sale, and purchase and buy (Chen, Guerrero, and Blaabjerg 2009).

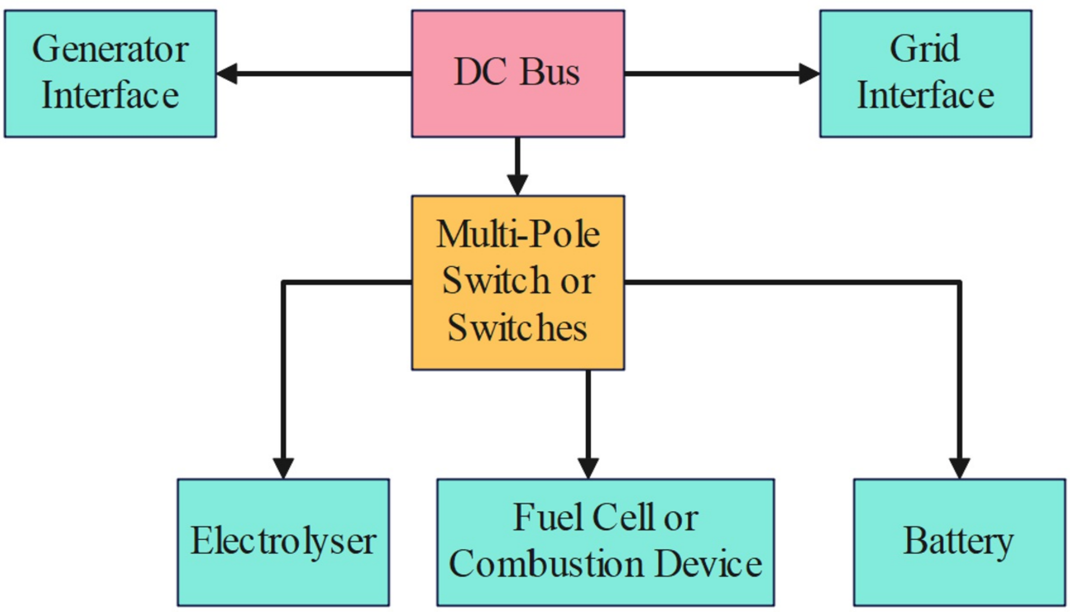

Figure 8. Full System Layout of the Power Electronics Configuration(Chen, Guerrero, and Blaabjerg 2009).

For the optimisation of the full system layout, the size of the components, how they are controlled, and some turbine design parameters are the variables shown in **Figure 8**.

Without significantly complicating the electrical energy control system, a modern variable-speed wind turbine can be connected to a number of hydrogen generating and consuming equipment. Reusing existing wind turbine components can considerably lower the cost of the complete system. Grid integration, which can lower the capacity of transmission lines and increase the network's capacity factor, is an additional advantage of a wind energy system with an integrated hydrogen system. Additionally, to deploy a wind farm, when necessary, weaker systems could need additional battery power or hydrogen-based renewable energy sources. Only a few of the potential include removing unused systems, increasing output, improving performance, and offering an application-specific design that is optimised.

6. Anion Exchange Membrane Electrolyser and Water Electrolysis for Low-Carbon Hydrogen Economies

Low-temperature water electrolysis, a promising energy conversion technology for intermittent electricity, can produce hydrogen. While PEM water electrolysis has advantages but is constrained by the acidic environment, alkaline liquid electrolyte water electrolysis is corrosive and sensitive to carbon dioxide(Zeng and Zhao 2015; Michael A. Hickner, Herring, and Coughlin 2013). The viability of both systems on a wide scale requires improvement. The use of mild alkaline solutions and even clean water is possible with the new water electrolysis method known as the anion exchange membrane (AEM), which lowers capital expenditure and operational costs for high economic value in low-carbon hydrogen energy production (Hagesteijn, Jiang, and Ladewig 2018).

However, AEM water electrolysis has drawbacks, including poor performance in terms of hydroxide ion conductivity and chemical stability. AEMs have hydroxide ion conductivities between 103 and 102 Scm^{-1}, which are insufficient for real-world uses (Miyata 1983; M. Ma et al. 2017; Hunter et al. 2016). AEMs also require laborious, intricate synthesis procedures that take a long time; include chemicals that are highly carcinogenic and poisonous; and have unstable functional groups. The conductivity, stability, and toxicity problems of AEMs must therefore be addressed throughout the preparation procedure. Figure 7 displays the rhombohedral crystal structure of LDHs, which have the formula $(Mg_{0.667}Al_{0.333})$ $(OH)_2(CO_3)_{0.167}.0.5H_2O$ (Dekel 2018; Varcoe et al. 2014; Tongwen and Weihua 2001). Each unit has a host layer and an interlayer. The host layer is made up of Mg^{2+} octahedra coupled to shared hydroxyl edges, with Al^{3+} replacing some of the Mg^{2+} to create a positively charged layer. The intercalated anions and water molecules within the interlayer play an important role in hydroxide ion conduction. Mg-Al LDHs were synthesised using a two-step approach involving coprecipitation and hydrothermal processes and structural analysis for the future of AEM electrolysis for efficient and affordable low-carbon hydrogen generation.(Gottesfeld et al. 2018; Merle, Wessling, and Nijmeijer 2011)

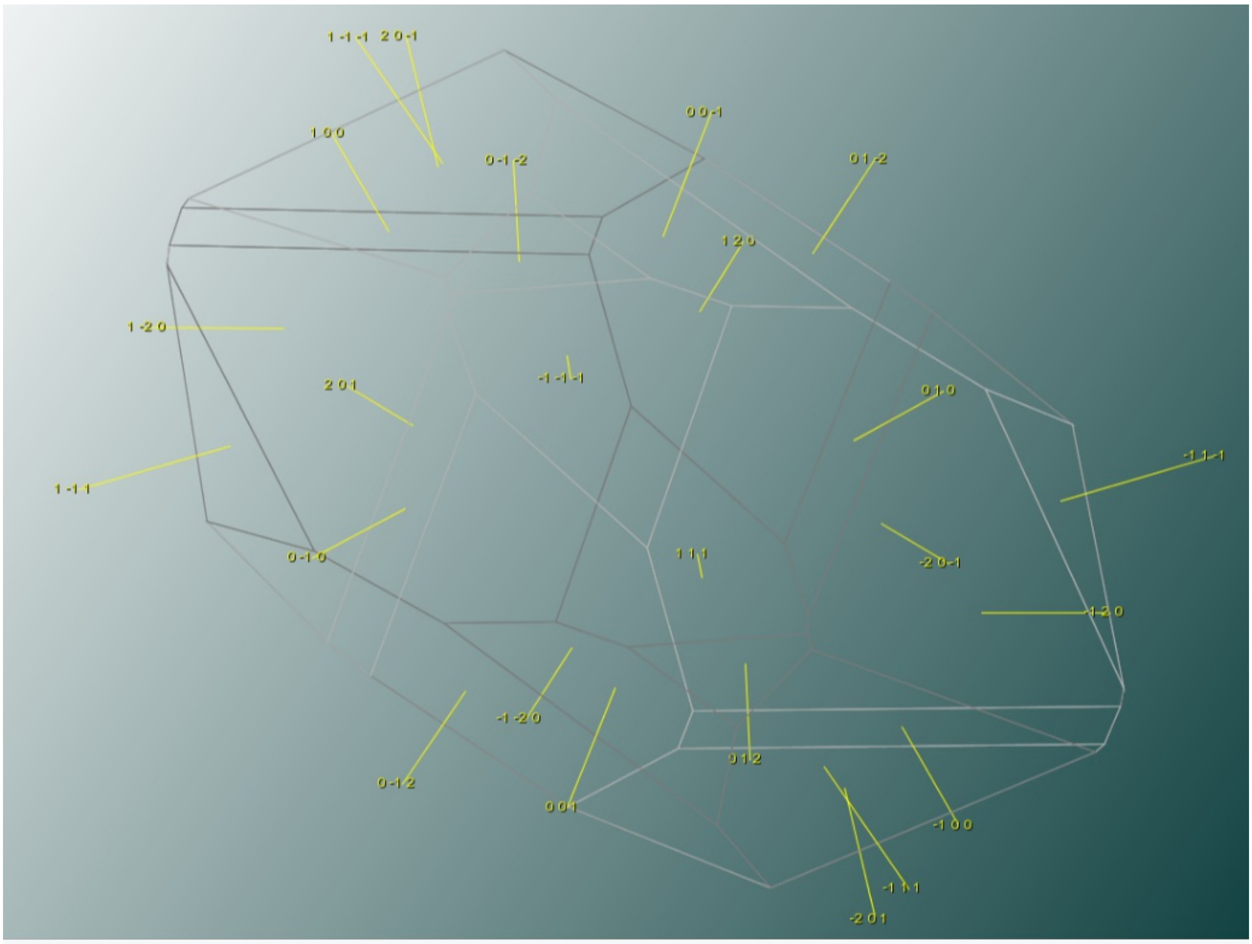

Figure 9. Mg-Al LDH crystal structure (JCrystal Software)(Merle, Wessling, and Nijmeijer 2011)

Figures 10A and **10B** indicate that conductivity increases as temperature and RH increase, with a maximum conductivity of 10.3 mS cm^{-1} occurring at 80.1 °C and a RH of 98% (H. Yan et al. 2019; N. Han, Zhao, and Li 2015; Nejati et al. 2018; Xu et al. 2015). This difference is caused by the uniform particle size and high crystallinity of the Mg-Al LDHs, which enable the conductivity of hydroxide ions along the interlayers, as well as the absorption of water by the LDHs (Vaselbehagh et al. 2017; Zhou et al. 2018; Z. Yan et al. 2018). After 200 hours, the inorganic membrane still had a hydroxide conductivity of 7.7 mS cm^{-1} **[Figure 10C]** (Xue et al. 2019; H. A. Miller et al. 2020), indicating that it is stable long-term enough for AEM water electrolysis(Bauer, Strathmann, and Effenberger 1990). Intercalated anions and absorbed water, which are not attacked by hydroxide anions, help hydroxide ions move across interlayers. This implies that the inorganic membrane is stable enough over the long run to support AEM water electrolysis (Mustain et al. 2020; Vincent and Bessarabov 2018; Li and Baek 2021).

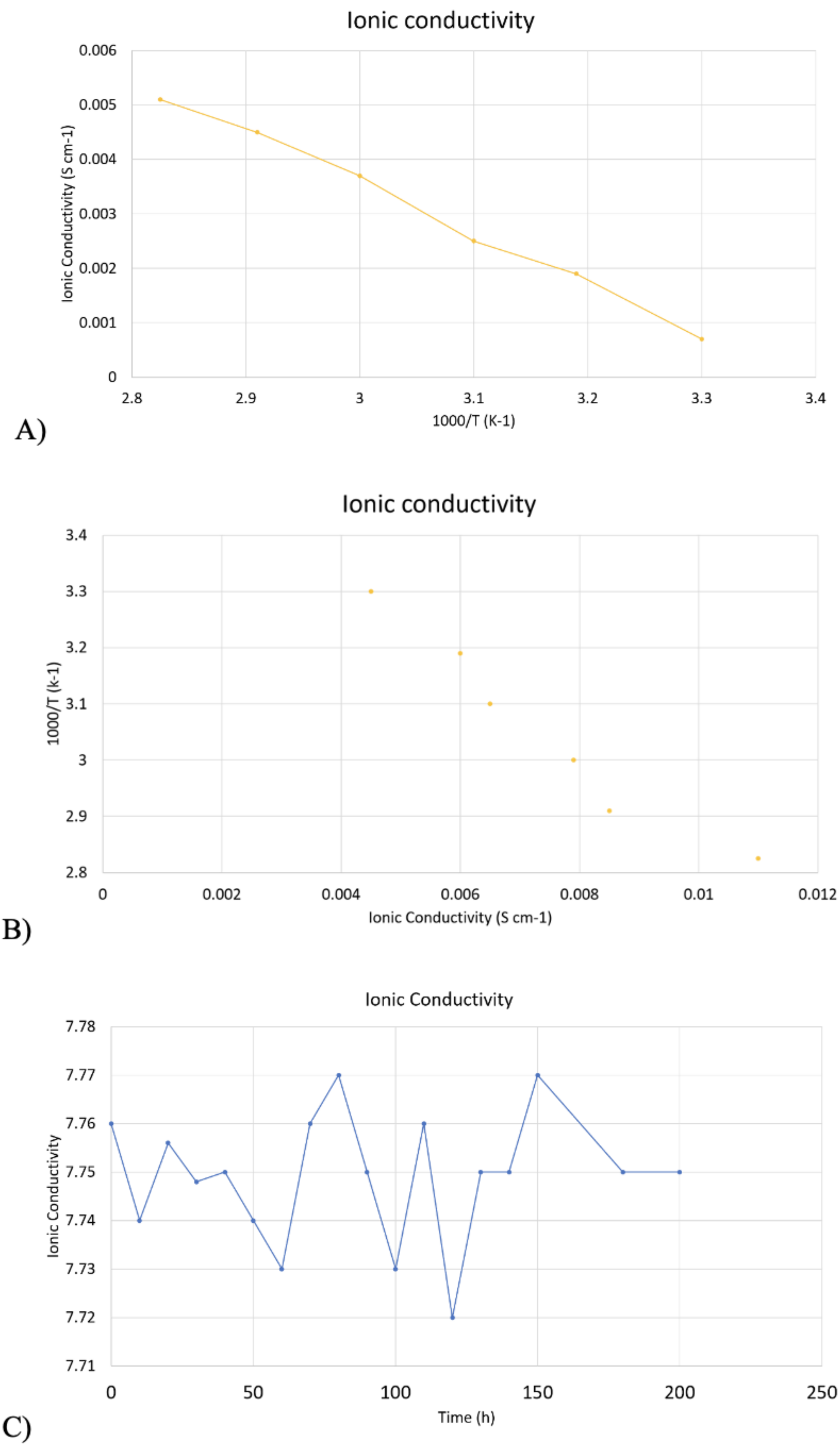

Figure 10. A) Conductivity of the Mg-Al LDH membrane at Ea=14.89 kJ mol $^{-1}$ and RH= 80%, B) conductivity of the Mg-Al LDH membrane at Ea= 12.27 kJ mol^{-1} and RH=98%, and C) conductivity stability test at RH=98% and 60.1C (X.

Yang et al. 2018; H. A. Miller et al. 2020; Dang et al. 2018; Zeng and Zhao 2015).

The I2MEA system is more reliable than the other systems and may operate electrocatalytically for AEM water electrolysis, according to the experimental results. The maximal current density is 208 mA cm^2, the cut-off voltage is 2.2 V at 70 °C, and the electrolyte is 0.1 M NaOH. The system was electrolyzed with 0.1 M NaOH and 0.1 M Na_2CO_3 for 600 hours, during which only a slight amount of degradation occurred. A method for manufacturing solid electrolyte-based, all-solid-state energy storage devices, such as solar cells, lithium-ion batteries, and supercapacitors, is provided by this technique (Zakaria and Kamarudin 2021; G. Huang et al. 2020; Vincent, Lee, and Kim 2021).

An appealing method for producing hydrogen at the site of use is water electrolysis employing anionic conductive solid polymer electrolytes. Alkaline devices are becoming increasingly competitive with their acidic counterparts due to recent developments in anion exchange membranes (AEMs) and catalysts (H. A. Miller et al. 2020; Parrondo et al. 2014; Vincent, Kruger, and Bessarabov 2017). Anion conduction ion analysers (ACIs) used to make electrodes for AEM electrolysers, however, have received less attention. To create oxygen-producing anodes for low-temperature AEM water electrolysis, a number of poly(norbornene)-based ionomers were created, characterised, and utilised in the process. The IEC of the ionomers (0 to 4.73 meq g^{-1}) was adjusted by controlling the ratio of the ionic-conducting norbornene monomers to the nonionic conductive monomers in the ACI tetrahedral copolymer (Dong et al. 2019).

In the absence of ACI polymer crosslinking, low-conductivity ionomers have been proven to produce the best performing oxygen evolution electrodes. When WU is supplied, light crosslinking in the ACI solution and cell performance considerably benefit from the highly conductive ionomer in the oxygen evolution reactive electrode. To create oxygen-growing electrodes for low-temperature AEM electrolysers, a range of poly(norbornene) tetrablock copolymers and homopolymers have been created. These materials have highly diverse ion exchange capabilities. It was discovered that ionomers with low or no IEC performed better than those with very high IEC and ionic conductivity. The reason for the subpar performance has been determined to be excessive swelling of the high IEC ionomer (T. Huang et al. 2022).

Table 1. Properties of poly(norbornene ionomers) (Leonard et al. 2023).

Sample	Mn (kDa)	Đ	IEC (meq g^{-1})	Ionic Conductivity (mS cm^{-1})	Column1	σ/IEC (g S/cm eq) (80 °C)	WU (%)
				25 °C	80 °C		
GT0	84.45	1.11	0	ND	ND	ND	ND
GT11	84.73	1.62	0.69	0.47	0.79	1.14	3.7
GT18	36.53	1.38	1.13	5.8	11.6	10.3	15
GT32	114.9	1.42	1.88	62	123	65.4	63
GT38	50.77	1.54	2.21	51	102	46.2	71
GT74	40.35	1.26	3.56	80	160	44.9	103
GT75	73.8	1.51	3.63	99	201	55.4	119
GT82	57.7	1.41	3.88	109	212	54.6	122
GT100	23.31	1.42	4.73	66	148	31.3	89

As shown in **Table 1**, tests were performed on nine poly(norbornene)-based ACIs with IEC values ranging from 0 to 4.73 meq g^{-1}. The letters GTXX, where XX denotes the mole percent of tetra block copolymer ionomers with quaternary ammonium headgroups, are used to identify the ionomer samples. Both a fully ionic homopolymer (GT100) and a nonionic homopolymer (GT0) with no ionic conductivity were used in this experiment. The physical properties of the ionomers are shown in **Table 1** based on measurements taken in film form (Leonard et al. 2023). Conductivity and water uptake tests for GT0 were omitted due to the absence of ion conduction.

A proper AEM electrolysis configuration, as shown in **Figure 11,** was used to showcase the associated and respective half-cell reactions in the anode and cathode as well as the overall reaction, which has E_0= 1.23 V.

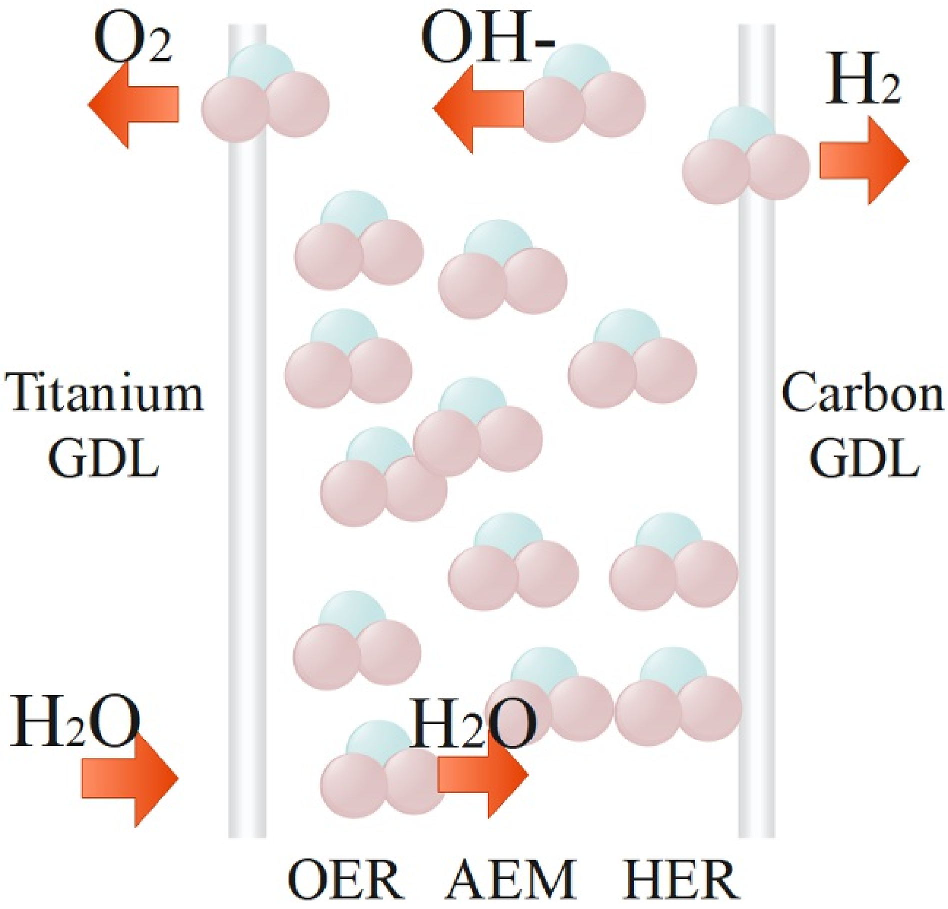

Figure 11. Configuration of the low-temperature AEM electrolysis cell configuration and associated half-reactions.

Anode: $4OH^{-} \rightarrow O_2 + 2H_2O + 4e^{-1} \quad E_0 = 0.401$ V

Cathode: $4H_2O + 4e^{-1} \rightarrow 2H_2 + 4OH^{-} \quad E_0 = -0.828$ V

Overall: $2H_2O \rightarrow 2H_2 + O_2 \quad E_0 = 1.23$ V

A modest amount of hydrophobic PTFE was first added to control the water concentration in the catalyst bed. Limiting ICA swelling with the use of light cross-linking inside an OER ioniser is more effective than using other methods, and this approach also enables the oxygen growing electrode to benefit from the superior conductivity of high IEC ion generators. Ionomers with a high IEC crosslink have the same WU as those with a low IEC crosslink (Varcoe et al. 2014; Miyata 1983).

Ultrapure hydrogen can be generated by an AEM electrolyser, which is regarded as a renewable energy resource system (>99.999% purity). The system is categorised as a "green energy system" since it uses water splitting to make hydrogen and oxygen when electricity is given, generating electricity without any pollutants. Additionally, hydrogen generation can be carried out whenever convenient and at any location where it can be used or stored immediately. In actuality, the direct use of hydrogen produced by an electrolytic device is best suited for fuel cells(H. A. Miller et al. 2020). The cost of manufacturing high-pressure bottled petrol could be decreased with this technology. Although the AEM electrolyser has a great deal of promise for producing hydrogen as a source of energy in the future, numerous issues must be resolved before a functioning system can be created. To provide the greatest performance for AEM electrolysers in the production of green hydrogen, the characterisation of alkaline solid polymer films as AEM components was fully studied in this study(Vincent, Lee, and Kim 2021). Several important properties have been described, including ion exchange capacity, ionic conductivity, chemical and mechanical stability, and cell performance endurance. Much work remains to be done to find the best alkaline solid polymeric membrane alternative, such as the AEM, for AEM electrolysers (Miyata 1983).

7. Proton Exchange Membrane Electrolysis Cells for Low-Carbon Hydrogen Generation

There has been much research on fuel cells fuelled by pure hydrogen or other fuels, particularly fossil fuels, as a result of the development of clean energy sources and the decrease in greenhouse gas emissions. Due to their weak reactivity, direct oxidising fuel cells (DOFCs), such as direct methanol fuel cells (DMFCs) or direct ethanol fuel cells (DEFCs), are still capable of only a limited amount of electrocatalytic oxidation of alcohols (Pei et al. 2014; J.-M. Park et al. 2015). One method for using primary energy sources from biomass, such as ethanol, is to electrochemically decompose them into hydrogen using electricity from nuclear power plants or other clean energy sources (Klingan et al. 2014). The most complex way to make hydrogen is through electrolysis of water, which produces high-quality hydrogen suitable for refuelling low-temperature fuel cells such as PEMFCs or AFCs, which generate electricity(Wee 2007; M. A. Hickner and Pivovar 2005; Shao et al. 2007; Jiao et al. 2021). Commercial fertilisers frequently have considerable energy efficiency (60–70%). The bulk of anodic catalysts are constructed from valve oxides (IrO_2, RuO_2, TaO_2) mounted on a titanium plate, much like the DSA-type electrodes developed for the chlor-alkali industry (Kang et al. 2019; B. Han et al. 2015a; Lamy et al. 2014a). Despite this, manufacturing costs are substantially higher than those of industrial procedures because of the significant overvoltage that occurs during water electrolysis (Oh 2016; Y. Yu et al. 2012; Lin et al. 2015). The amount of energy required to produce 1 kilogram of hydrogen is significantly greater than that which was projected (33 kWh kg^{-1} under ideal conditions), up to approximately 50 kWh kg^{-1} (equal to approximately 4.5 kWh^{kg-1}). The detailed cross-sectional schematic of a PEMEC, as shown in **Figure 12,** shows a two-dimensional single-channel repeat unit in a dashed box unit (Z. Ma et al. 2021).

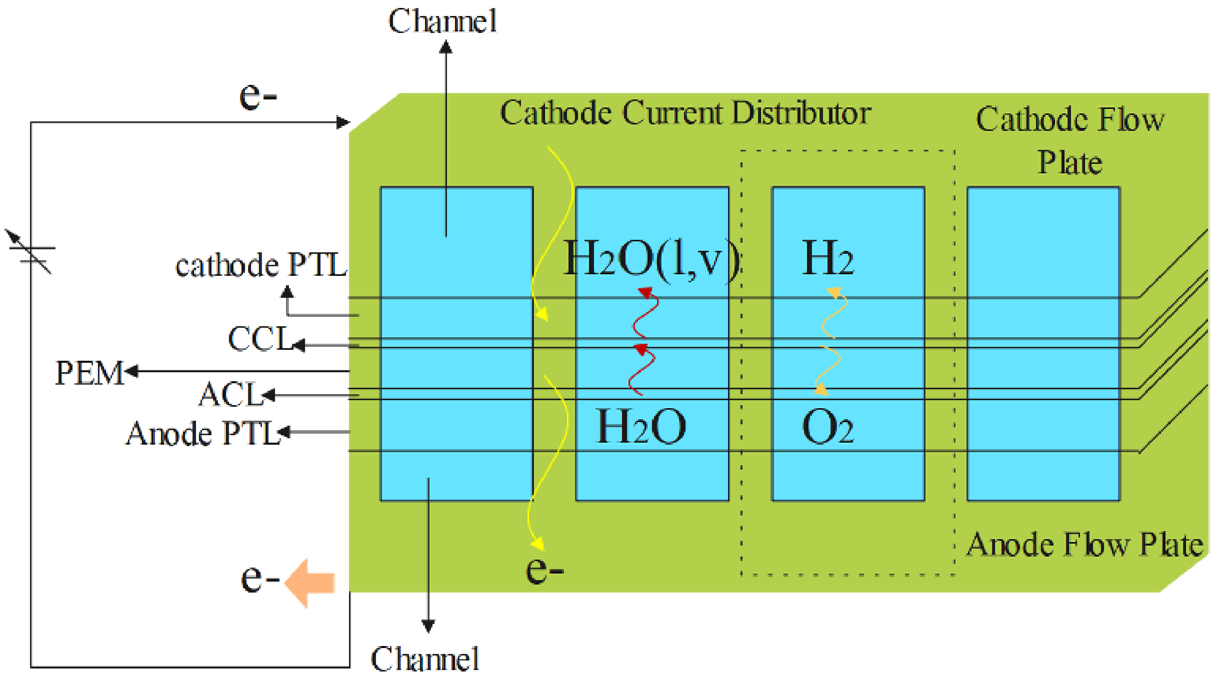

Figure 12. Cross-sectional view of PEMECs (Z. Ma et al. 2021)

Since the theoretical cell voltage for the electrochemical decomposition of organic molecules is lower than the theoretical cell voltage of water, another strategy that uses biomass feedstock (instead of water) as a source of hydrogen appears to be very promising. Although organic biomass-derived raw materials, including alcohols, carboxylic acids, sugars, etc., have been taken into account as hydrogen sources, there has been very little research on the electrochemical breakdown of organic molecules (B. Han et al. 2015b; 2017). For the anodic oxidation of ethanol, pt-based catalysts have been studied because they can provide fast reaction rates at low voltages. In addition to water, numerous other hydrogen-containing substances can dissociate to create hydrogen, particularly organic substances derived from biomass. In comparison to the hydrogen produced by thermal processes such as SR, ATR, and PrO_x, the electrochemical breakdown of water or an organic substance generates hydrogen of significantly greater quality and does not necessitate further exhaust gas purification. since none of the other gases (CO, CO_2, etc.) were present. Water electrolysis is a process that is almost complete, although it requires a large amount of energy (w^5 kWh $(Nm^3)^{-1}$) (Lamy et al. 2014b).

Proton exchange membrane fuel cells (PEMFCs) have many advantages over other types of fuel cells, including low operating temperatures, sustained performance at high energy density, compactness, cost potential, low mass, long battery life, quick startup, and suitability for intermittent operation. These features make PEMFCs the most appealing and prospective contenders for a variety of energy application fields, including transportation, stationary uses, and mobile ones (Lamy et al. 2014b; Salari, Hakkaki-Fard, and Jalalidil 2022). However, before PEMFCs can be effectively commercialised in each of these fields, a number of problems still need to be solved (Salari, Hakkaki-Fard, and Jalalidil 2022; Awasthi, Scott, and Basu 2011; G. Yang et al. 2017). Every other problem requires a reliable and affordable supply of H_2 (i.e., the production of high-purity H_2 and stable storage with a safe fuel phase). This unique technical lock has not yet been entirely broken, despite the efforts of numerous researchers (Wee, Lee, and Kim 2006; Luo et al. 2021). $NaBH_4$ hydrolysis, a H_2 delivery and storage option in PEMFCs, has recently gained popularity due to its favourable qualities for portable PEMFC applications, as shown in **Table 2**. When the system is combined with a PEMFC ($NaBH_4$-PEMFC), the following additional advantages can be realised:

Table 2. Advantages of the $NaBH_4$ hydrolysis reaction as a H_2 supplier and during storage (GARRON et al. 2009).

As the source of H2	Advantageous features
Generation	– On-site generation of H_2 – Only occurs in the presence of selected catalysts and reaction rates are easily controlled by the catalysts – Carried out even at 0 °C – Sufficiently high purity of H_2
Storage and safety	– Theoretical hydrogen content of $NaBH_4$ solutions is 10.9 wt.% – Volumetric and gravimetric H_2 storage efficiencies are high – $NaBH_4$–NaOH aqueous solutions are stable in air for months and nonflammable
Reaction Mixture	– The reaction products including $NaBO_2$ are environmentally safe and can be recycled back to NaBH4 using coke or methane

Pure Pt can be used as a positive electrode catalyst for PEMFCs. The lack of a separate processor for cleaning allows for simplification of the PEMFC system. The H_2 pressure/flow rate can be carefully controlled and self-regulated using a variety of feedback methods. $NaBH_4$ can be readily recharged by simply filling the tank with new $NaBH_4$ solution. The NaBH4-PEMFC system consists of two phases (Dragan 2022). The development of a low-cost $NaBH_4$ hydrolysis mechanism with a high reaction efficiency and optimal reaction rate is the initial stage. Second, a strong system design should be used to link this hydrogen supply to the PEMFC. However, most people concur that the first question is the most important. It is still unclear whether the amount of H_2 produced and the reaction rate are sufficient to power PEMFCs, although multiple studies on the hydrolysis of $NaBH_4$ to produce H_2 have been published. These technological problems have recently been theoretically and experimentally resolved, at least in part (Brack, Dann, and Wijayantha 2015). However, before we could use the $NaBH_4$-PEMFC system in a useful way, we had to overcome many challenges. These included the kind and quantity of the catalyst being employed, the quantity and concentration of the $NaBH_4$ solution, the reaction temperature, and other variables. Studying system design, handling products, and catalyst inactivation are also essential subjects. The $NaBH_4$-PEMFC system cannot be used widely due to the high cost of $NaBH_4$ ($55/kg). This price is 130 times greater than that of converting natural gas to hydrogen and 50 times greater than that of generating hydrogen by electrolysis of wind energy. However, if the price of $NaBH_4$ drops due to widespread production and recycling of the reaction product, $NaBO_2$, the system might emerge as a key contender in the portable and lightweight

PEMFC industry. $NaBH_4$ can be synthesised according to previous research by reacting $NaBO_2$ with MgH_2 or Mg_2Si and annealing H_2 at high pressure. A simple method is to combine MgH_2 with $Na_2B_4O_7$ and then ball grind it at room temperature (Patel, Fernandes, and Miotello 2009).

The creation and manufacture of an ideal catalyst are the most crucial steps in using the H_2 produced by the hydrolysis of $NaBH_4$ as a fuel for PEMFCs. With typical H_2 generation rates ranging from 0.1 to 2.8 H_2 l min^{-1} g^{-1} and a PEMFC efficiency ranging from 0.1 to 0.3 kW g^{-1}, various catalytic systems have been presented. It has also been noted that a Pt/carbon (acetylene black) catalyst with a very high H_2 generation rate of 28 l min^{-1} g^{-1} (catalyst) corresponds to a PEMFC output power of 0.3 kW. Consequently, the $NaBH_4$-PEMFC system appears to be a technically sound substitute for fuel cell H_2 delivery.

8. Conclusion

A proper transitional low-carbon hydrogen energy economy is needed for rapid research and development both computationally and experimentally. Through the compound annual growth rate and global investments in a low-carbon hydrogen circular economy, we determined that the global market demand for hydrogen will increase, but one of the drawbacks is that most production occurs through the use of conventional energy feedstocks, which need to be altered to renewable energies according to the United Nations' sustainable development goals.

One of the workable technologies for producing environmentally friendly low-carbon hydrogen is electrochemical water splitting. The employment of an electrolyser, a water electrolysis cell, makes this hydrogen processing sustainable. By enhancing the power grid, this electrolyser can be utilised in conjunction with a wind energy source, such as a windmill, to aid in the creation of H_2. Alkaline and proton exchange membrane electrolysers have advanced to the advanced commercial level in the hydrogen processing industry in recent decades. Unfortunately, both methods have a number of significant drawbacks, including how hydrogen is handled, the size of the structures, and the high cost of the materials required to build the cells. To function properly, the $NaBH_4$-PEMFC system needs a large amount of $NaBH_4$ and has a fast reaction rate. The system design must take the power of the PEMFC into account to control the H_2 generation rate and amount. For the purpose of clearing the mists, an additional humidifier is needed.

Due to their high hydrogen storage density, ability to construct compact microcells on a large cell scale, and use of nonplatinum and nonnafion membrane materials, anion exchange membrane (AEM) electrolysers have been suggested as a solution to the worst aspects of prior electrolyser types. An important element that affects the effectiveness of an AEM electrolyser, which functions as an anion exchange membrane (AEM), is the solid polymer alkaline membrane. The AEM functions as an ion transfer channel, an anode and cathode separator, and a barrier to electron movement. Finding a suitable alkaline solid polymer electrolyte for an AEM electrolyser is being presented as a research direction. Finding the most promising polymeric materials to create alkaline solid polymer membranes is the key problem. Shortening ionic diffusion and reducing reactant crossover are necessary for realising superior ionic conductivity performance. Due to the additional ionic pathways and higher ionic exchange capacity, functional groups are a great way to increase the ionic conductivity. Finally, alkaline solid polymer electrolytes must maintain the functioning of the AEM electrolyser.

Due to the current advances in energy transition, there is a dire need to substitute fossil fuels with several cleaner, sustainable and zero net emissions fuels, one of which is hydrogen generation for a sustainable economy.

Acknowledgements

The authors equally acknowledge the Indian Institute of Technology, Madras, and the University School of Chemical Technology, Guru Gobind Singh Indraprastha University, for providing excellent research facilities and a supportive atmosphere. The authors would also like to acknowledge MOKSH Research and Development for providing all necessary support during this research.

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